

Construction and Test of the Precision Drift Chambers for the ATLAS Muon Spectrometer

F. Bauer, W. Blum, U. Bratzler, H. Dietl, S. Kotov, H. Kroha, Th. Lagouri, A. Manz, A. Ostapchuk, R. Richter, S. Schael

Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 Munich, Germany

S. Chouridou, M. Deile, O. Kortner, A. Staude, R. Ströhmer, T. Trefzger

Ludwig-Maximilians-Universität, Schellingstraße 4, D-80799 Munich, Germany.

Abstract—The Monitored Drift Tube (MDT) chambers for the muon spectrometer of the ATLAS detector at the Large Hadron Collider (LHC) consist of 3–4 layers of pressurised drift tubes on either side of a space frame carrying an optical deformation monitoring system. The chambers have to provide a track position resolution of $40\ \mu\text{m}$ with a single-tube resolution of at least $80\ \mu\text{m}$ and a sense wire positioning accuracy of $20\ \mu\text{m}$ (rms). The feasibility was demonstrated with the full-scale prototype of one of the largest MDT chambers with 432 drift tubes of 3.8 m length. For the ATLAS muon spectrometer, 88 chambers of this type have to be built. The first chamber has been completed with a wire positioning accuracy of $14\ \mu\text{m}$ (rms).

Keywords—Drift tubes, drift chambers, muon spectrometer, ATLAS detector

I. INTRODUCTION

The muon spectrometer of the ATLAS experiment [1] will be operated in the toroidal magnetic field of a superconducting air-core magnet system with 3–6 Tm bending power. It is designed to provide stand-alone muon momentum resolution of $\Delta p_T/p_T = 2 - 10\%$ for transverse momenta between 6 GeV and 1 TeV over a pseudo-rapidity range of $|\eta| \leq 2.7$. This requires very accurate track sagitta measurement with three layers of muon chambers and high-precision optical alignment monitoring systems. Precision drift chambers, the Monitored Drift Tube (MDT) chambers, have been developed to provide a track position resolution of $40\ \mu\text{m}$ over an active area of $5500\ \text{m}^2$.

The MDT chambers (see Fig. 1) consist of 3 or 4 layers of precise aluminum drift tubes with $29.970 \pm 0.015\ \text{mm}$ outer diameter and $400\ \mu\text{m}$ wall thickness on either side of a space frame carrying an optical monitoring system to correct for chamber deformations. The drift tubes are operated at a gas pressure of 3 bar to provide a single-tube position resolution of at least $80\ \mu\text{m}$ (rms) with an Ar:CO₂ (93:7) gas mixture and at the low gas gain of 2×10^4 required to prevent ageing of the drift tubes at the high background rates at the LHC. The sense wires of the drift tubes have to be positioned in individual tubes with an accuracy of $10\ \mu\text{m}$ (rms) and in the whole chamber with an accuracy of $20\ \mu\text{m}$

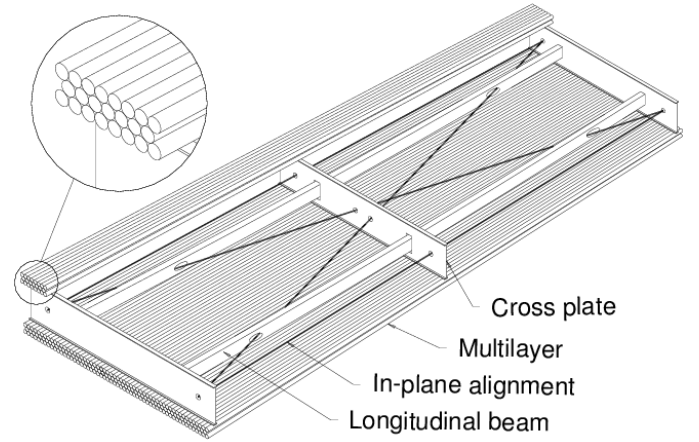


Fig. 1
MONITORED DRIFT TUBE (MDT) CHAMBER FOR THE ATLAS MUON SPECTROMETER.

(rms) in order to obtain a chamber position resolution of $40\ \mu\text{m}$ (rms).

In total 1200 MDT chambers containing 400000 drift tubes of 1–6 m length have to be constructed for the ATLAS muon spectrometer at 13 production sites over a period of 4 years. In Munich, the production of 88 of the largest MDT chambers with 432 drift tubes of 3.8 m length in 6 layers and with a width of 2.16 m has started. The drift tubes for these chambers are fabricated in a joint facility at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. The first MDT chamber for the ATLAS detector (named ‘BOS-0’) has been completed in August 2000.

In spring 1998, the full-scale prototype of a MDT chamber of this type (named ‘BOS 98’) has been built with the methods developed for large-scale production [1]. With the prototype chamber, it has first been demonstrated that the required high mechanical accuracy can be achieved. Over the last two years, operation experience with MDT chambers was gained with the prototype in the muon test beam at CERN.

Corresponding author: H. Kroha, Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 Munich, Germany (e-mail: kroha@mppmu.mpg.de).

Permanent address of F. Bauer: CEA Saclay, DSM, DAPNIA, F-91191 Gif-sur-Yvette Cedex, France.

Permanent address of S. Kotov: Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia.

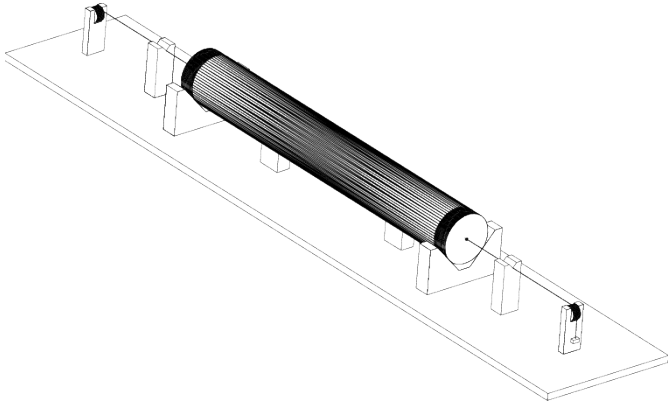


Fig. 2

WIRE POSITIONING METHOD FOR THE DRIFT TUBES OF THE PROTOTYPE CHAMBER.

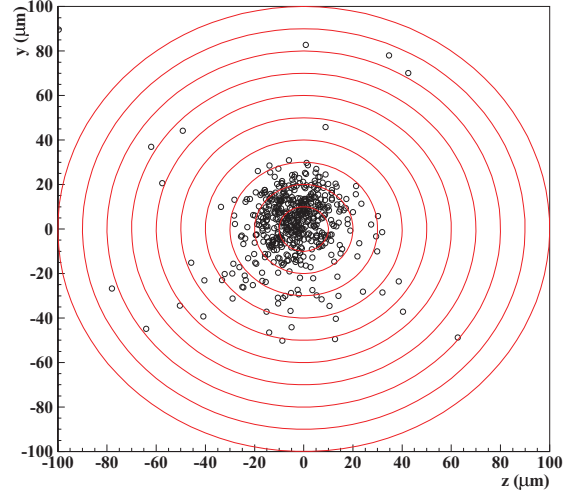


Fig. 4

WIRE POSITIONING ACCURACY WITH THE GLUEING TECHNIQUE.

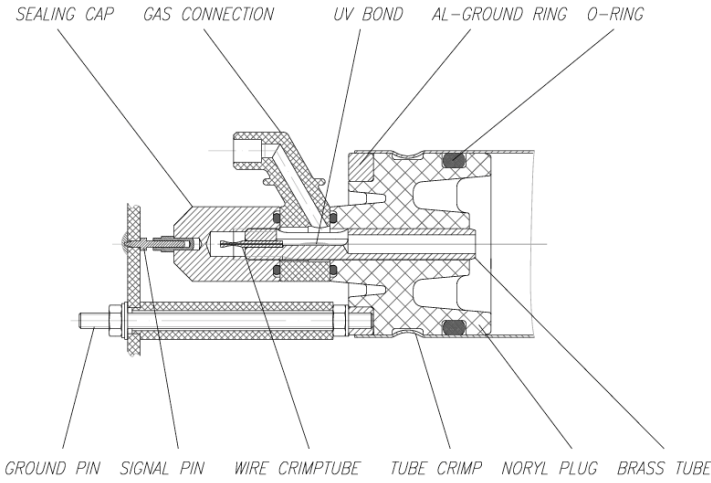


Fig. 3

ENDPLUG FOR THE GLUEING TECHNIQUE FOR PRECISE WIRE LOCATION. THE WIRE IS GLUED IN THE GROOVE OF THE CENTRAL BRASS TUBE.

II. DRIFT TUBE FABRICATION

For the prototype chamber, the sense wires were positioned and fixed at the tube ends using external references for tubes and wire and fast-curing glue (see Fig. 2). The effect of glue shrinkage on the wire position was measured and taken into account. The endplug of the drift tubes designed for this method (see Fig. 3) does not require high precision in the fabrication. After assembly, the wire positioning accuracy at the ends of the drift tubes with respect to the outer tube diameter was measured to be $10 \mu\text{m}$ (rms) in both coordinates including the non-roundness of the tubes (see Fig. 4) using a stereo X-ray technique with a resolution of $2 \mu\text{m}$.

For the large-scale production, a precisely machined endplug variant (see Fig. 5) has been adopted where the wire is

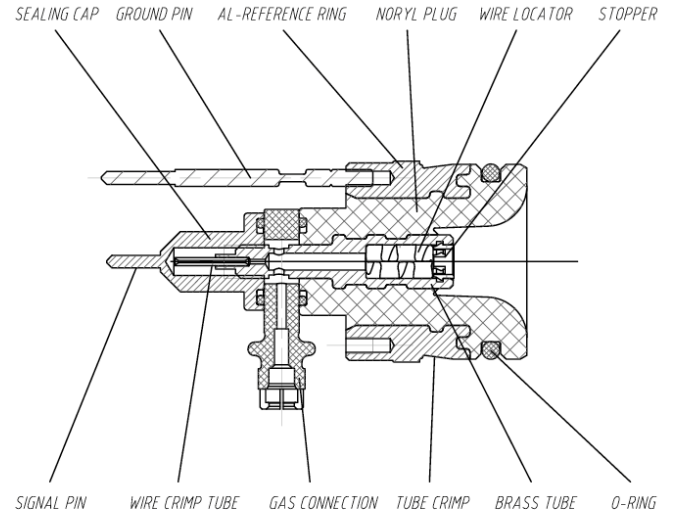


Fig. 5

ENDPLUG WITH PRECISE MECHANICAL WIRE LOCATION WITH RESPECT TO THE ALUMINUM REFERENCE RING.

located in a spiral hole concentric with an aluminum reference ring on which the drift tube ends are positioned during chamber assembly (see below). The injection moulding process of the insulating plastic (Noryl) body of the end-plugs with the metal inserts has been carefully optimised in order to prevent stresses and the development of cracks which can make the drift tubes leak. The X-ray measurements show a wire positioning accuracy of $7 \mu\text{m}$ (rms) (see Fig. 6).

Reliable ground contact of the aluminum tubes (the cathodes of the drift tubes) is provided by spot welds to the aluminum ring on the endplug using a specially developed

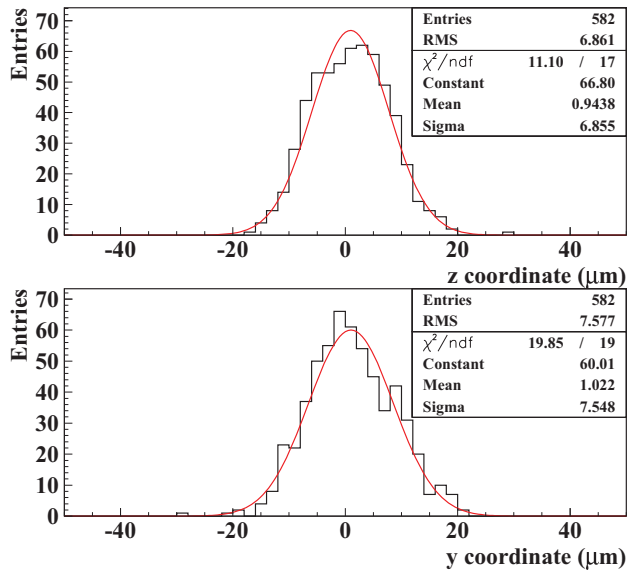


Fig. 6

WIRE POSITIONING ACCURACY IN INDIVIDUAL DRIFT TUBES WITH THE PRECISE ENDPLUGS USED FOR CHAMBER SERIAL PRODUCTION IN THE Z COORDINATE PARALLEL TO THE TUBE LAYERS (TOP) AND IN THE Y COORDINATE PERPENDICULAR TO THE TUBE LAYERS (BOTTOM).

laser welding technique employing filler wire. The contact resistance at a current of 10 mA stays below 1 m Ω even after an accelerated corrosion test with exposure to salt spray for 48 hours.

The drift tubes for serial production are assembled semi-automatically in a clean room of class 10000 with temperature and relative humidity controlled to be $(20 \pm 0.5)^\circ\text{C}$ and $(50 \pm 10)\%$, respectively. They have to fulfil stringent quality criteria which include wire position measurement with X-rays within $\pm 2.5\sigma$ ($\sigma = 10 \mu\text{m}$) in both coordinates, gas leak rate at 3 bar below $10^{-8} \text{ bar} \cdot \text{l/s}$, wire tension within $\pm 5\%$ of the nominal value of 350 g, and high voltage leakage current for Ar:CO₂ (93:7) at 3 bar and 3.4 kV below 8 nA. At present, the drift tube rejection rate is about 3%.

In the drift tubes of the BOS 98 and the BOS-0 chamber, the wire tension, determined from the measurement of the oscillation frequency ν of the 50 μm diameter gold-plated tungsten-rhenium (97:3) wire, is uniform within 2% (rms).

III. CHAMBER ASSEMBLY

During the assembly of a MDT chamber [1], the ends of the drift tubes for each layer are positioned on precision aluminum combs with an accuracy of 3 μm (rms) in horizontal (z) and vertical (y) direction. The combs have been produced industrially by spark erosion and are installed on a flat granite table in a clean room of class 100000 with temperature and relative humidity controlled to be $(20 \pm 0.5)^\circ\text{C}$ and $(50 \pm 10)\%$, respectively. Over their whole length the tubes are held straight in 9 parallel rows of combs with vacuum suction.

The tube layers inserted in the combs are glued subsequently to the aluminum space frame (three cross plates connected by two long beams; see Fig. 7) which for this purpose is positioned with respect to the combs with an

TABLE I

GEOMETRICAL CHAMBER PARAMETERS (SEE TEXT) FROM THE FIT TO THE X-RAY MEASUREMENTS (WITH RMS ERRORS) IN COMPARISON WITH THE DESIGN VALUES (WITH ABSOLUTE TOLERANCES)

BOS 98 High Voltage End		
Parameter	X-ray fit	Design value
y -pitch [μm]	26058 ± 0.5	26054 ± 5
z -pitch [μm]	30036.2 ± 0.5	30036 ± 0.5
Δy [mm]	347.041 ± 0.011	347.040 ± 0.010
Δz [μm]	-8 ± 11	0 ± 10
BOS 98 Readout End		
Parameter	X-ray fit	Design value
y -pitch [μm]	26060 ± 1.3	26054 ± 5
z -pitch [μm]	30036.2 ± 0.5	30036 ± 0.5
Δy [mm]	347.078 ± 0.012	347.072 ± 0.010
Δz [μm]	3 ± 16	0 ± 10
BOS-0 High Voltage End		
Parameter	X-ray fit	Design value
y -pitch [μm]	26039 ± 0.5	26039 ± 5
z -pitch [μm]	30035.8 ± 0.5	30036 ± 0.5
Δy [mm]	346.878 ± 0.005	346.882 ± 0.010
Δz [μm]	-22 ± 5	0 ± 10
BOS-0 Readout End		
Parameter	X-ray fit	Design value
y -pitch [μm]	26041 ± 0.5	26039 ± 5
z -pitch [μm]	30035.8 ± 0.5	30036 ± 0.5
Δy [mm]	346.852 ± 0.005	346.882 ± 0.010
Δz [μm]	-9 ± 5	0 ± 10

accuracy of $\pm 5 \mu\text{m}$ in y and z on precision towers at the ends of the three cross plates (see Fig. 7). The positioning of the space frame is monitored with laser beams and transparent optical position sensors [2]-[5].

While the space frame is supported on the reference towers during glueing of a tube layer, the 2.16 m wide cross plates of the large chambers bend between the support points under the weight of the chamber by up to 80 μm at the ends and 100 μm in the middle. The gravitational sag of the cross plates during assembly is measured with optical sensors installed on the cross plates (see Fig. 8). In order to prevent deformations of the tube layers after glueing them to the space frame, the cross plates are also supported via the long beams applying forces with computer controlled pneumatic actuators until the sag is compensated without lifting the chamber from the reference towers. After positioning the chamber on the reference towers, the pneumatic actuators instantaneously apply the required forces at the ends of 4 bars inserted through holes in the long beams close to the cross plates as shown in Fig. 7.

IV. X-RAY MEASUREMENTS OF THE CHAMBERS

The wire positions in the completed chambers have been measured at CERN [6] with scans with stereo X-ray sources perpendicular to the wires. The reproducibility of the X-

TABLE II

WIDTHS (RMS) OF THE WIRE COORDINATE RESIDUAL DISTRIBUTIONS

BOS 98 Chamber			
	High voltage end	Readout end	Center
y -coord. [μm]	19.0 ± 0.8	17.0 ± 0.2	15.0
z -coord. [μm]	19.3 ± 0.8	18.2 ± 1.3	16.1
Combined [μm]	18.4		15.6
BOS-0 Chamber			
	High voltage end	Readout end	Center
y -coord. [μm]	14.3	15.3	13.2
z -coord. [μm]	10.5	14.1	7.7
Combined [μm]	13.6		10.5

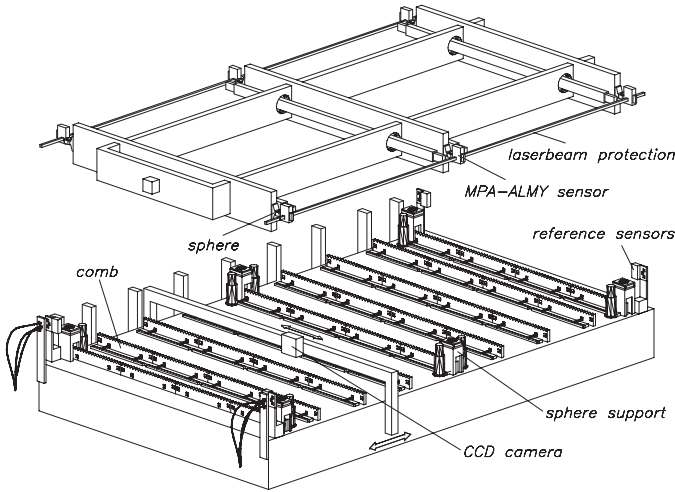


Fig. 7

CHAMBER ASSEMBLY TABLE WITH PRECISION JIGS, SPACE FRAME WITH BARS FOR CROSS PLATE SAG COMPENSATION (SEE TEXT) AND OPTICAL MONITORING DEVICES.

ray measurements of the wire coordinates was within $5 \mu\text{m}$ (rms) during the scans of the prototype chamber in 1998 and now is within $3 \mu\text{m}$ (rms).

A fit of an ideal wire grid to the measured wire coordinates y (perpendicular to the tube layers) and z (parallel to the tube layers) allows a determination of the geometrical parameters of the chamber and to evaluate the wire positioning accuracy. In Table I the fitted parameters, the horizontal (z) and vertical (y) wire pitch (at $20 \pm 0.5^\circ\text{C}$) and the y - and z -separations Δy and Δz between the two triple-layers, from the scans at the chamber ends are compared to the design values for the prototype chamber (BOS 98) and for the first production chamber (BOS-0). For the BOS 98 chamber, the X-ray results are the average of several scans at the same position along the tubes. The Δy values at both ends of this chamber differ because of a known com-

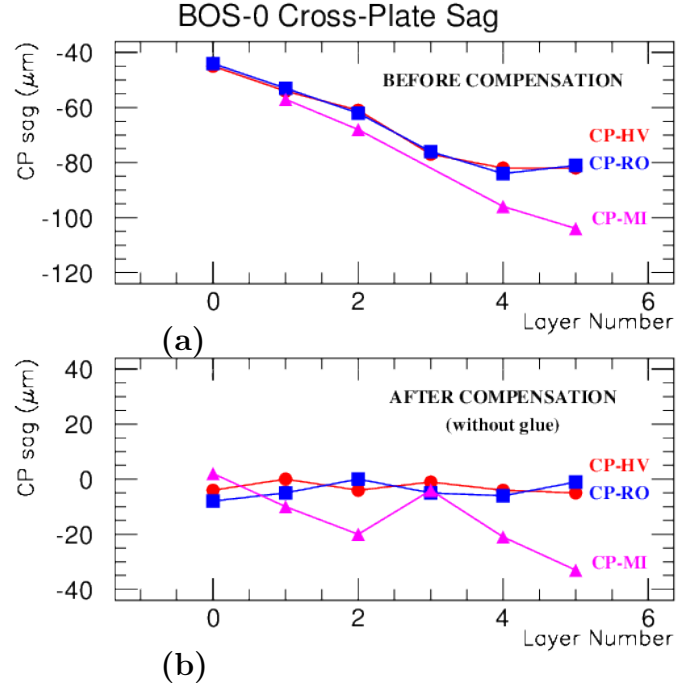


Fig. 8

GRAVITATIONAL SAG OF THE CROSS PLATES AT THE HIGH VOLTAGE (HV) AND READOUT (RO) ENDS AND IN THE MIDDLE (MI) OF THE BOS-0 CHAMBER AS A FUNCTION OF THE NUMBER OF TUBE LAYERS GLUED TO THE SPACE FRAME (A) BEFORE AND (B) AFTER THE COMPENSATION (HV: CIRCLES, RO: SQUARES, MI: TRIANGLES).

mon y -offset of the wire positions in the tubes at the readout end. During the assembly of the BOS-0 chamber, an unexpectedly large shrinkage of the glue between tube layers and frame was observed which is taken into account in the design values. With the different type of glue used for the BOS 98 chamber, no significant glue shrinkage was observed. For both chambers, the fitted parameters agree very well with the design values.

Distributions of the residuals of the measured wire coordinates y and z with respect to the fitted grid are shown in Figs. 9 and 10 for the two chambers. The widths of the distributions for X-ray measurements at both ends of the chambers as well as near the center are summarised in Table II. The wire locations at intermediate positions between the tube ends are determined by the wire locations at the ends (weighted averages) and by the gravitational sag s of the wires. The wire sag is known from the measurement of the wire oscillation frequency ν via the relation $s = \frac{g}{32\nu^2}$ where g is the gravitational acceleration. Variations in the maximum wire sag of 2% (rms) of the nominal $195 \mu\text{m}$ due to the variations of the wire tension are negligible.

The residuals of the y -coordinates are shown in Figs. 11 and 12. The gravitational sag of the cross plates which has to be compensated for the assembly of each tube layer (see Fig. 8) is indicated. The BOS-0 chamber, for cost reasons, has less stiff cross plates than the prototype chamber and therefore larger cross plate sag. The statistical fluctuations

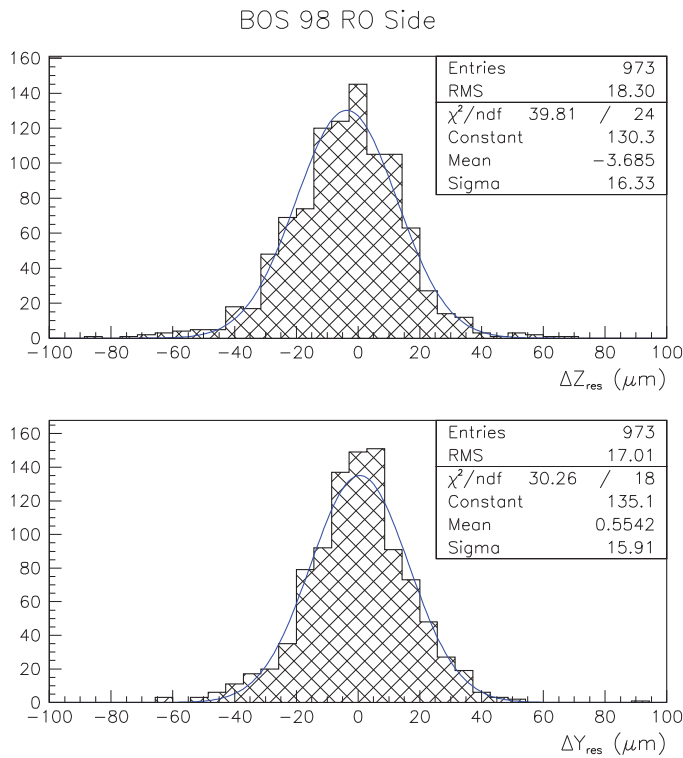


Fig. 9

DISTRIBUTIONS OF THE RESIDUALS OF THE MEASURED WIRE POSITIONS WITH RESPECT TO THE FITTED GRID AT THE READOUT END OF THE BOS 98 PROTOTYPE CHAMBER IN THE Z COORDINATE PARALLEL TO THE TUBE LAYERS (TOP) AND IN THE Y COORDINATE PERPENDICULAR TO THE TUBE LAYERS (BOTTOM).

of the wire locations are larger in the prototype chamber because the aluminum tube walls, instead of the precise endplugs, were used as references for the positioning of the drift tubes

The wire positioning accuracy in the prototype chamber is better than the required $20 \mu\text{m}$ (rms). With the first production chamber, a wire positioning accuracy of better than $14 \mu\text{m}$ (rms) has been achieved for one of the largest chamber types in the ATLAS muon spectrometer. The main improvement with respect to wire positioning accuracy compared to the prototype chamber is the introduction of the aluminum reference ring on the endplugs which allows more precise positioning of the drift tube ends on the assembly combs than the aluminum tube walls used before. Based on the present experience, a wire positioning accuracy of about $10 \mu\text{m}$ (rms) is reachable for such large chambers.

V. TEST BEAM MEASUREMENTS

The prototype chamber has been tested in a 300 GeV muon beam at CERN at perpendicular incidence to the tube layers. Ar:CO₂ (93 : 7) at 3 bar was used as drift gas. Using a silicon strip detector telescope as external reference, the space to drift-time relationship and the position resolution as a function of the drift distance r have

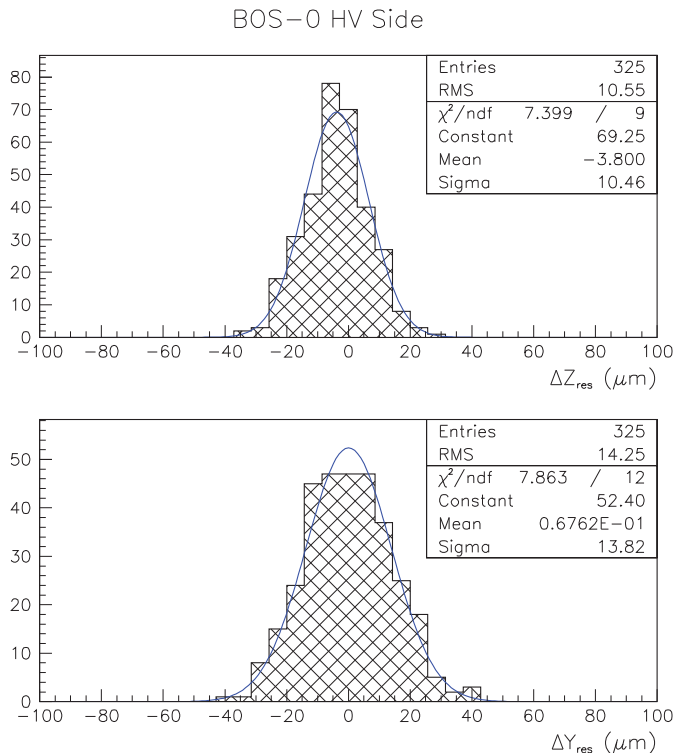


Fig. 10

AS FIG. 9 FOR THE HIGH-VOLTAGE END OF THE BOS-0 CHAMBER.

been determined. (see Fig. 13). The average single-tube resolution at the low interaction rates is $70 \mu\text{m}$ (rms).

The r - t -relationship measured locally was applied to the other drift tubes in the beam allowing only the maximum drift time to vary within $\pm 6 \text{ ns}$ (rms) because of varying operating conditions. Requiring the track residual distributions as function of the drift distance to be symmetric left and right of the wires provides information about displacements of the wires from their nominal positions in z -direction with respect to a reference wire. Comparison with the X-ray measurements of the z -coordinates of the wires shows a good correlation (see Fig. 14). Both measurements agree within $10 \mu\text{m}$ (rms).

VI. ACKNOWLEDGEMENTS

We wish to thank our colleagues at the JINR, Dubna for the fabrication of such excellent drift tubes for the BOS-0 chamber and are indebted to the X-ray tomograph group at CERN for the prompt and accurate measurements of our chambers.

VII. REFERENCES

- [1] A. Airapetian, V. Grabsky, H. Hakopian, A. Vartapetian, F. Fares, G.F. Moorhead, et al., "ATLAS Muon Spectrometer

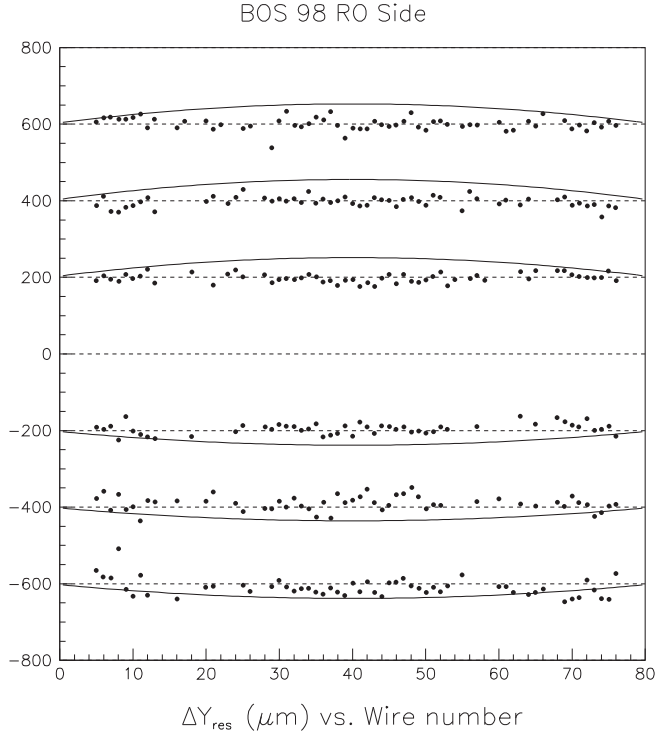


Fig. 11

RESIDUALS Δy_{res} OF THE MEASURED y COORDINATES OF THE WIRES IN THE 6 TUBE LAYERS (DISTANCES BETWEEN LAYERS COMPRESSED) WITH RESPECT TO THE EXPECTED WIRE GRID AT THE READOUT END OF THE BOS 98 PROTOTYPE CHAMBER. THE UNCOMPENSATED CROSS PLATE DEFORMATIONS DURING ASSEMBLY OF EACH LAYER ARE INDICATED.

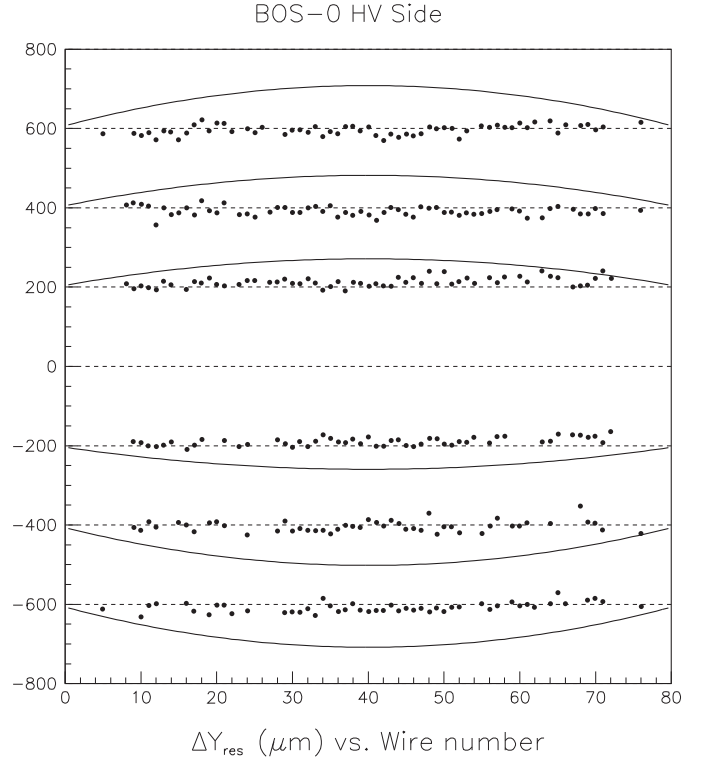


Fig. 12

AS FIG. 11 FOR THE HIGH-VOLTAGE END OF THE BOS-0 CHAMBER.

- Technical Design Report," CERN, Geneva, Switzerland, CERN internal report, CERN/LHCC/97-22, May 1997.
- [2] W. Blum, H. Kroha, and P. Widmann, "A novel laser alignment system for tracking detectors using transparent silicon strip sensors," *Nucl. Instr. Meth.*, vol. 367, pp. A413-A417, 1995.
 - [3] W. Blum, H. Kroha, and P. Widmann, "Transparent silicon strip sensors for the optical alignment of particle detector systems," *Nucl. Instr. Meth.*, vol. 377, pp. A404-A408, 1996.
 - [4] W. Blum, H. Kroha, and P. Widmann, "A novel laser-alignment system for particle tracking detectors using transparent silicon strip sensors," *IEEE Trans. Nucl. Sci.*, vol. 43, no. 3, pp. 1194-1199, June 1996.
 - [5] H. Kroha, "Laser-alignment system with transparent silicon strip sensors and its applications," *Nucl. Phys. B (Proc. Suppl.)*, vol. 54, pp. B80-B85, 1997.
 - [6] J. Barbiers, D. Drakoulakos, C.W. Fabjan, S. Grau, E. Gschwendtner, J.-M. Maugain, et al., "High-precision X-ray tomograph for quality control of the ATLAS muon monitored drift chambers," *Nucl. Instr. Meth.*, vol. 419, pp. A342-A350, 1998.

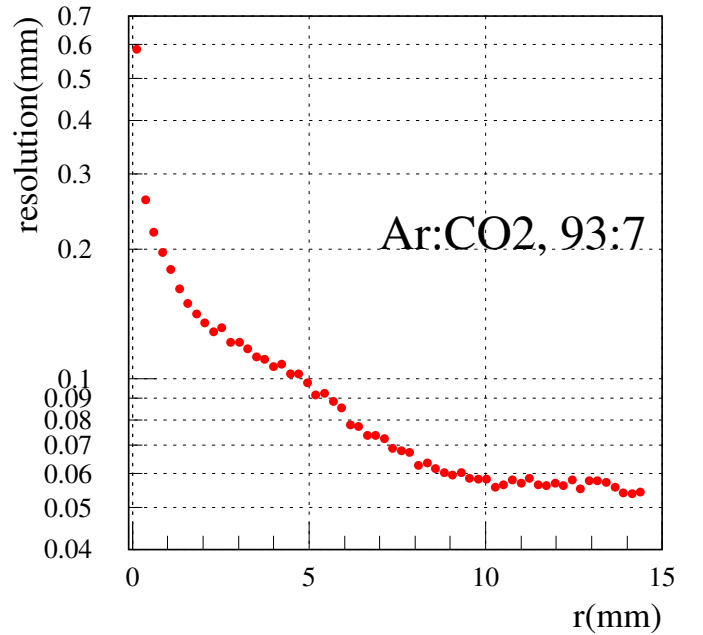


Fig. 13

SINGLE-TUBE RESOLUTION AS A FUNCTION OF DRIFT DISTANCE FOR AR:CO₂ (93:7) GAS MIXTURE AT 3 BAR.

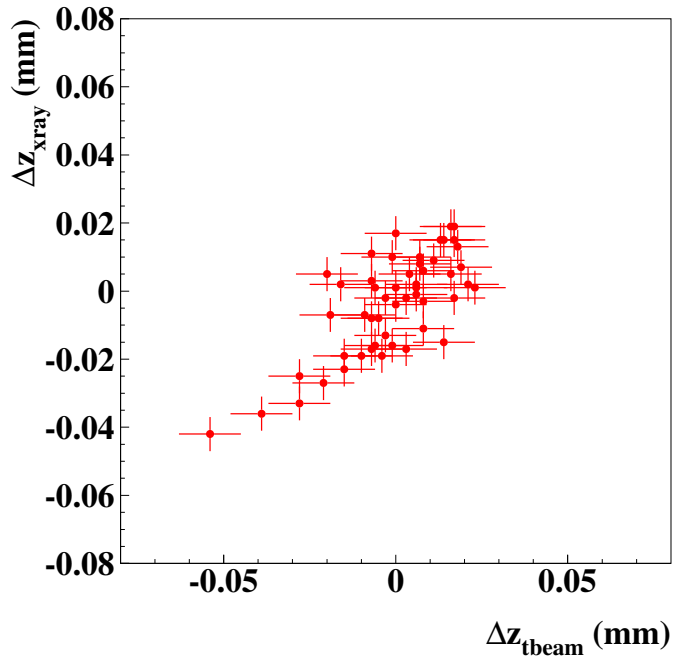


Fig. 14

CORRELATION BETWEEN THE WIRE COORDINATE MEASUREMENTS
WITH X-RAYS AND WITH MUON TRACKS FROM THE TEST BEAM.